Increasing Aviation Safety Using Human Performance Modeling Tools: An Air Man-machine Integration Design and Analysis System Application

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Abstract

Human Performance Modeling (HPM) tools are computational, human-out-of-the-loop (HOOTL) representations of several micro models of operator-environment performance used to predict complex human-system interactions. HOOTL processes provide economical (in terms of time and money) means of studying complex human-system performance. As technologies and automation increase to assist the human operator in the increasingly cognitively demanding world, human-related vulnerabilities may arise that may impact the system safety by increasing procedural error rates. Hollnagel's conceptualization of human error will be used as the theory behind a HOOTL simulation currently underway at NASA Ames Research Center to predict human error in the aviation environment in surface operations [1]. One of the HOOTL simulation tools being used to generate human-system performance predictions is the emergent HOOTL tool termed Air Man-machine Integration Design and Analysis System (MIDAS). This paper will outline the current understanding of factors underlying human error and the considerations that need to be heeded in developing HOOTL simulations for human-automation predictions. These HOOTL simulations will be shown to be effective means of predicting system vulnerabilities and will allude to possible intervention strategies.

BACKGROUND AND INTRODUCTION

Two methods exist for studying human performance in complex systems: Human-in-the-loop (HITL) high-fidelity simulations or computational human-out-of-the-loop (HOOTL) predictive simulations. The use of HITL simulation has been proposed as a methodology for examining human-systems performance in a safe and controlled environment in the surface transportation and aviation communities [2]. This technique has proven to be successful in accomplishing the goal of safely and realistically evaluating human-system behavior but has the disadvantage of being very complex and costly, often times prohibiting its use. In contrast, HOOTL simulations can be less expensive and used at an earlier process in the development of a product, system or technology. HOOTL simulation tools are computer-based simulation processes where human characteristics, taken from years of research from respective fields, are embedded within a computer software structure to represent the human operator interacting with computer-generated representations of the operating environment [2,3,4]. The human characteristics in many of the integrated HOOTL simulation tools include visual and auditory perceptual and attentional systems, anthropometric characteristics, and environmental characteristics (including workstations as well as the outside environment). These structures feed-forward and feedback with the goal of predicting human behavior. These complex integrated HOOTL simulation tools permit researchers to formulate procedures, generate and test hypotheses, identify variables for upcoming HITL simulations, and refine the procedures to ensure that they can be successfully completed in the time allotted for the given environmental demands. The output measures of interest for HOOTL simulation efforts from the aviation community generally include workload and timing measures. These measures have been validated across multiple domains: helicopter operations [5,6,7], nuclear power-plant control electronic list design for emergency operations [8], and advanced concepts in aviation [9,10].

Integrated human performance models (HPM) a form of HOOTL simulation, include procedural static models of human performance, anthropometric models of human performance, complex, dynamic representations of human performance, and cognitive performance [11]. A number of model representations are required to create the dynamic model representation. The dynamic representation of human performance requires the developer to create static representations of the overall task structure that is performed by the agent in the simulation. Since the human operator is simulated, the risks to the human operator and the costs associated with system experimentation are greatly reduced: no experimenters, no subjects, and no testing time. One criticism of HOOTL tools is that the software only predicts input-output behavior in mechanistic terms.[1] Gore and Corker indicate that the integrated structure of the tools does more than solely represent input-output behavior [13]. The framework integrates many aspects of human performance allowing each micro model component to behave in its required method, the integration of which replicates a human

[1] For further discussion of the advantages and disadvantages of HPM, please consult [2].

Cognitive Modeling Development

One fundamental component within the integrated HPM is the cognitive component and many of the HPMs are now attempting to augment their cognitive representations due to increases in cognitive demands associated with recent advances in the operational environment. Cognitive modeling concepts were integrated into the engineering models' philosophy in order to assist in predicting complex human operations. The overall philosophy behind the use of cognitive modeling was to provide engineering-based models of human performance. The engineering-based models of human performance permit a priori predictions of human behavior of a very restricted set of behaviors in response to specific tasks. Human performance modeling has traditionally been used to predict sensory processes [15], aspects of human cognition [16], and human motor responses to system tasks [3,17,18]. Human performance modeling tools are currently undergoing another developmental shift. The attempt now is for the HPM to be sensitive to situations that confront a virtual human in systems similar to the HITL situations. The growth in human performance modeling has been to examine human performance in systems including system monitoring (thereby taking information in from the environment) as opposed to the closed-loop view of the human as a mathematical relationship between input and output to a system. In fact, human-computer simulation modeling programs have been proposed to study human performance interacting with systems, and to support prediction of future system state [19]. These hybrids of continuous control, discrete control and critical decision-making models have been undertaken to represent the "internal models and cognitive function" of the human operator in complex control systems. These hybrid systems involve a critical coupling among humans and machines in a shifting and context sensitive function. The Man-machine Integration Design and Analysis System (MIDAS) is an example of such a hybrid tool that utilizes an emergent behavior approach to modeling an individual's performance [2].

MIDAS' general structure is made up of interconnected systems that interact with each other in a closed-loop fashion (Figure 1). Objects in MIDAS exchange messages through agent architectures. MIDAS' agent architecture is made up of physical component agents and human operator agents [8]. Physical component agents can use commercially available computer-aided design (CAD) databases to graphically represent physical entities in an environment. Physical world agents are the external environments such as terrain and aeronautical equipment. The human operator agents are made up of human performance representations of cognitive, perceptual and motor operations of a task. These models describe within their limits of accuracy the responses that can be expected of the human operator. The attention demands are based on Wickens' Multiple Resource Principle [20] and incorporate a task loading index created by McCracken-Aldrich for quantifying attention [21] along the visual, auditory, cognitive and psychomotor (VACP) resources. In addition, MIDAS possesses degradation functions that incorporate the effect of stressors on skill performance through Rasmussen's skill-, rule- and knowledge-based decisions [22].

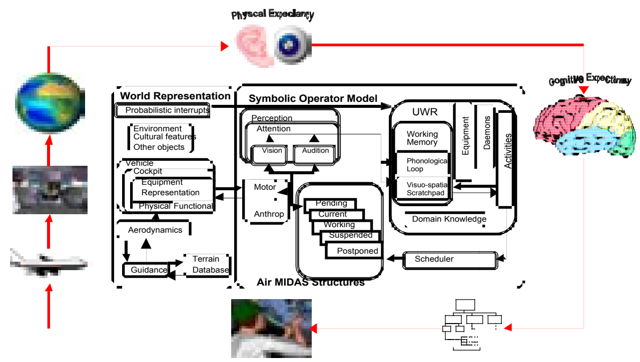

Figure 1. Air Man-machine Integration Design and Analysis System (MIDAS).

The main components of the emergent model shown in Figure 1 comprise the simulated representation of the real world that characterizes the virtual operator modeled by MIDAS, and a symbolic operator model (SOM) that represents perceptual and cognitive activities of a MIDAS agent. Information passes from the outside world into the agent's cognition through vision and audition. The structure known as the Updateable World Representation (UWR), an important if not critical element of the SOM represents the cognitive operation of the agent. The world representation information (environment, crew-station, vehicle, physical constraints and the terrain database) is passed through the SOM's perception and attention to the UWR. This is being done in much the same way that the human operates. The UWR represents the agent's working memory (WM), domain knowledge and task activity structure to be completed. The agent's UWR also contains an expectation function that is designed to represent attentional, perceptual and cognitive attributes (such as orientation) that are completed during procedure engagement [13,23]. The UWR passes information to a scheduler within the SOM that determines the resources available for the completion of the activity. MIDAS uses a procedurally based language invoking a series of predetermined goal-oriented behaviors (tasks). The environment triggers activities (procedures) within the virtual operator who then completes the desired procedure in accordance with their resource availability, their goals and their priorities. The scheduler invokes rules to determine the procedural triggers. Procedures can be postponed, suspended, working, current, or pending. In turn the SOM selects activities to perform, some of which interact with the representation of equipment in the simulated world and change the behavior of the relevant part of the system. This series of actions and interactions among the structures within the HOOTL software is key when attempting to model perceptions and interpretation (characteristics of human cognition) of information from the world state. These perceptions and interpretations impact the physical performance of a task because without perception and interpretation of the external environment, there cannot be an accurate response of the virtual operator.

Air MIDAS is a computational framework that has augmented MIDAS' conceptual mechanisms and behavioral structures to include multi-crew communication, intent inferencing logic, a notion of expectation among agents in the simulation, contextual performance effects and operator affect [17]. Air MIDAS has also become compliant with the US DoD Higher Level Architecture (HLA) requirements permitting cross-model integration. Some of the augmentations to the initial MIDAS software code have been created from a number of studies including free flight concept exploration and dynamic airspace re-sectrorization [3,24,25].

Human Performance and Automation

It is critical to understand the root causes behind the limitations in the human agent's abilities and the times that the system will cause the agent to approach these limitation levels. Simply increasing technologies and automation in complex systems to assist the human operator may not have the desired human performance effects of error reduction as increasing use of technology and automation in complex systems exceed the limited cognitive capacity of the human operator [26,27]. Furthermore, an incorrect reliance and use of these automated systems often results in different kinds of erroneous performance that has larger system-safety related effects [27]. Implementation of these technologies on a vast system-wide application without a full evaluation of the costs associated with such a transition would not be prudent. In order to augment and fully understand the interaction that often occurs with a human and automation, it is appropriate to develop and use human performance modeling tools to supplement HITL experimentation. As a starting point to develop and augment human performance simulation structures contained within the tools, it has been determined [1,28] that errors emerge as the human operator approaches their limit in abilities and as a function of the context in which the operator is performing.

Human Performance and Contextual Effects

Hollnagel refines Reason's [28] concept of active-latent organizationally defined human error causation to one that is specifically aimed at predicting human error in cognition [1]. He indicates that cognitive errors can be viewed according to how they account for the underlying causes of actions. Hollnagel indicates that erroneous behavior can be viewed as resulting from sequential/ procedural errors or contextual factors. The procedural model of cognition is a normative model indicating how a task should be carried out. Any deviation to this plan results in an error. The contextual control model (CoCoM) of cognition concentrates on how the control action selection occurs, rather than focussing on the adequacy of the sequences of actions for attaining the goal. Control action selection is impacted by automation in the human-system environment. Automation increases the reliance on human cognitive abilities for successful performance and these higher cognitive processes are characterized by higher error rates [1,27]. Given this relationship, it is being proposed that the use of cognitive modeling tools that possess validated memory representations will be useful in pinpointing vulnerable areas that are environmentally associated (contextual manipulations).

To date, HOOTL researchers have paid little attention to the environment's impact on the behavioral predictions generated by cognitive models and the link between the behaviors and the cognitive processes required by a given situation. One theory that attempts to provide a link between an environment's impact on the behavioral predictions generated by a cognitive model and the behavior-cognitive processing relationship required due to a given situation is Hollnagel's CoCoM through its cognitive processing module [1]. CoCoM states that a person's comprehension and action depends on how a context is perceived and interpreted. The purpose of the cognitive processing module within CoCoM is to meet a particular goal. This goal is satisfied by actively referring to the environment, to knowledge, or to cognitive processes as opposed to passively responding to the environment. WM plays into this process by storing contexts, which, in turn, trigger relevant answers. These WM modules are sequenced by WM storage. CoCoM views human performance as determined for the most part by the context that characterizes the environment of the human operator and the performance of the individual operator occurs as a result of the active planning ongoing by the individual operator in response to the environment. Hollnagel proposes that the actions that are carried out by the human can fail to achieve their goal as a result of accurate performance according to an inadequate plan (cognitive planning error) or deficient performance (physical error) in carrying out a successful plan. Hollnagel argues that research surrounding human error appears to confuse the causes of the events surrounding human error with the internal psychological processes or cognitive mechanisms that are presumed to explain the action (cause of event versus class of actions). CoCoM outlines the inter-relationship among internal cognitive mechanisms and control levels on behavioral outcomes. All of these mechanisms demonstrate the impact that context has on impacting the performance of the individual in the environment rather than by an inherent relation between actions.

Current Human Performance Modeling Effort

Current NASA research efforts have focussed on creating dynamic models of human performance and, more recently, on anticipating human errors that have significant system-level impact. A full mission simulation of current day surface operations at Chicago O'Hare [29,30] served as the basis to create the HOOTL HPM simulation. The pilot performance during current day operations will set the stage for comparisons to human performance when technological introductions are made. In order to generate a sufficiently valid representation of error predictions, the equipment, the crew-station and external environment was modeled at varying levels of fidelity depending on the information importance for updating the operator's world. As demonstrated at a very high level in Figure 2, three agents were modeled (at differing levels of fidelity). These interacting agents were modeled with different goals and responsibilities associated with their roles in system operations. It was determined that modeling three agents, the Tower Air Traffic Controller (ATC), the Captain (CA), and the First Officer (FO) provides a realistic modeling environment and exercises some of the multi-crew coordination mechanisms within Air MIDAS.

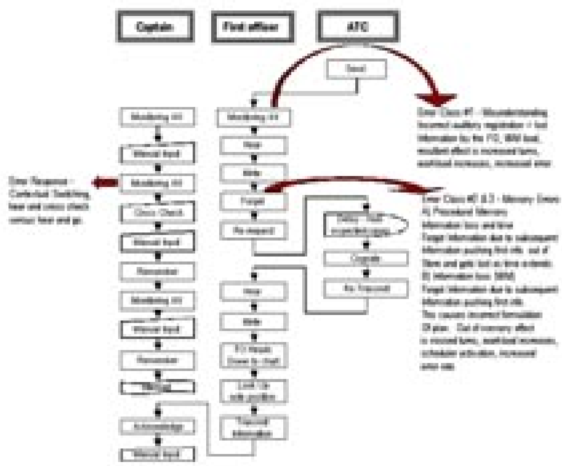

Figure 2. Overview of the scenario considerations guiding the development of human error within Air MIDAS.

A representation of the information-state of the crew-station was created in order to generate error patterns for the virtual operator based on the contextual information gained during the scenario. This representation required an attentional synchronization between the attention/perception module and the environment module of the scenario within Air MIDAS. This behavioral change is anticipated to occur due to the emergent behaviors that are elicited from the virtual operators in the environment.

Two facets exist in discussing the results of a HPM - the steps and assumptions made to create the model and the timeline and workload predictions output from the model. This paper focuses on the structural representations and the scenarios used to generate error predictions and the relationship this has with the HITL performance generated from simulation experiments. Three human error vulnerabilities in surface operations that impact safety guided model development - UWR error, procedural, and memory load errors. It is expected that each type of error will emerge as a result of the realistic scenario requirements and cognitive demands that are placed on the simulated operator and the occurrence of an error will invoke a contextual switching mechanism within one of the agents in the simulation.

The HITL surface operations simulation found that errors occurred when either the CA or FO misunderstood or misheard the taxi clearance [29,30]. The misunderstanding among the operators is representative of a mismatch between the cognitive structures of the operator's understanding of the environment and can be modeled as an UWR discrepancy in which there is a worldview inconsistency between two virtual operators in the environment. Replicating this class of error required the development of a rich environment and a relatively complex set of procedures. We accomplished this by building a full representation of the cockpit, of pilot-pilot interaction, of ATC-pilot interaction, and of the airport surface environment. A full set of realistic landing procedures were modeled including: environmental monitoring, changing radio frequency, contacting company for gate assignment, contacting ATC and listening to clearance, writing down the clearance, and inter-cockpit communication. The contextual error is expected to emerge when one virtual operator erroneously "thinks" a different virtual operator has received shared information. The UWR errors will manifest themselves in workload increases, response delays to currently ongoing tasks, and in time increases to complete a procedure. The expectation is for an increase in intra-cockpit communication (CA and FO), pilot-ATC communication, and increased negotiation between all crewmembers. This error vulnerability arises because of informational differences being provided to the operators and any subsequent increase in time to complete a series of actions will occur due to cognitive negotiation tactics that must occur between agent in the simulation to arrive at a consistent worldview.

The HITL surface operations simulation found evidence of errors occurring because operators omitted or substituted parts of a required taxi clearance to get to the gate, a procedural memory error [29]. These errors became apparent when the flight crew took a wrong turn on the airport surface. Replicating this class of error required the development of a rich environment and a relatively complex set of procedures designed to exercise the memory function of the Air MIDAS model. We accomplished this by building a full representation of the pilot-pilot, ATC-pilot interaction, and of the airport surface environment. A full set of realistic landing procedures were modeled including: environmental monitoring, changing radio frequency, resetting gear and flaps, contacting company for gate assignment, contacting ATC and listening to clearance, writing down the clearance, and intra-cockpit communication. The procedural interruption occurs when operators are faced with procedures that compete for procedural memory resources. These decay across time and can become lost **if** time extends beyond an acceptable upper time boundary (decrements by the WM decay rate on each tick of the Air MIDAS simulation). When the activation level falls below a retrievability threshold, the node attribute values become unretrievable and procedures fail. These high workload conditions were aimed at eliciting the error. Procedural memory errors therefore manifest themselves as dropped tasks and procedures, procedural re-starts, missed hold short bars and missed turns. These errors will increase the behavioral completion time and will impact the behavioral onset time.

The HITL simulation found evidence of errors occurring because demands were too high and pilot forgot part or all of the clearance [29]. This error type is indicative of a Working Memory (WM) Load Error. The WM Load Errors occur as a result of information competing for WM space. Air MIDAS will use existing mechanisms embedded within each virtual operator to replicate the WM Load Errors identified in the HITL simulation. When there are a number of items occupying WM, one item in WM may be shifted out of the limited capacity store by the subsequent information from the pilot or from the controller communication. Replicating this class of errors required exercising the communication agents within the Air MIDAS structure. We accomplished this by building a full representation of the cockpit, of pilot-pilot interaction, of ATC - pilot interaction, and of the airport surface environment. A full set of realistic landing procedures were modeled including: environmental monitoring, changing radio frequency, resetting gear and flaps, contacting company for gate assignment, contacting ATC and listening to clearance, writing down the clearance, and intra-cockpit communication. The information provided to the respective agent is lost from the "active" list, or the series of active procedures scheduled to occur, if it is not written down. Given that the human operator is characterized as a limited capacity store, items within this memory structure fall out of memory if not rehearsed. Rehearsal can occur by mentally recalling the required information bits, or when this is not available relying on some external visual aid like a list. The virtual operator was set to consult a list (notation of directions) in conditions when they lost information from within their cognitive store. The WM errors manifest themselves as differences in memory load and memory onset and finish times, dropped tasks, ongoing procedures and procedural interruption, visual workload increases and differences in workload patterns.

It is expected that each type of error will emerge due to scenario requirements and demands placed on the virtual operators. The requirements and demands impact the virtual operator's ability to form an appropriate cognitive plan given the availability of resources that the virtual operator can dedicate to the environmental conditions. The errors present themselves by the occurrence of scheduled and dropped procedures (procedures that never got finished) during the completion of the run, or missed/omitted procedures. There are some runs that do not get completed (representing an error) and there are other runs that do get completed (no error). The HITL error rate will be compared with the HOOTL prediction.

CONCLUSION

This paper demonstrates advances in computational cognitive modeling tools that attempt to create dynamic computational models of human error. A critical aspect of the methodology is the interaction that exists among the physical and cognitive structures in completing complex jobs. The identification of mechanisms involved in the creation of error will certainly lead to a better understanding of the concepts underlying human performance, and will lead to more solid computational predictive tools of human performance, especially in the increasingly complex and automated work environment. This computational analysis methodology permits the Human Factors Practitioner and Human Performance Modeler to generate a closer link between the job, the use of the automation and the human performer with their physical and cognitive abilities. This coupling is critical if the tools that are being generated today will be useful in accomplishing the ultimate goal of accurately predicting human performance in the increasingly complex, and cognitively demanding work domain.

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Biographies

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